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Fatigue Assessment of Orthotropic Steel Decks of Box Girder Bridges

Comportement à la fatigue des dalles orthotropes en acier
de ponts en caisson

Einschätzung des Ermüdungsverhaltens orthotroper Stahlfahrbahnplatten
von Hohlkasten-Brücken

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SUMMARY

This report shows a case study on fatigue assessment of orthotropic steel decks of box girder bridges typically used for urban elevated highway systems in Japan. Cumulative fatigue damage for several welded joints on the bridge are computed using design wheel loads and truck models that represent service truck traffic.

RÉSUMÉ

Cet exposé présente une étude de cas sur le comportement à la fatigue des dalles orthotropes en acier de ponts en caisson typiques des autoroutes urbaines surélevées au Japon. Le cumul du dommage en fatigue pour plusieurs joints soudés du pont a été estimé à l'aide des charges de roue normalisées et des modèles de camion représentant le trafic usuel de poids lourds.

ZUSAMMENFASSUNG

Der vorliegende Bericht behandelt eine Fallstudie zur Einschätzung des Ermüdungsverhaltens orthotroper Stahlfahrbahnplatten von Hohlkasten-Brücken, wie sie in Japan für städtische Hochstrassen verwendet werden. Für Norm-Radlasten und Lastmodelle, die den Schwerverkehr darstellen, wird die Schadensakkumulation an verschiedenen geschweissten Verbindungen der Brücke berechnet.



1. INTRODUCTION

The orthotropic steel decks are susceptible to fatigue cracking when they are subjected to extremely heavy truck traffics [1, 2]. Actually, a few fatigue cracks have been observed in orthotropic steel decks, some of which are shown in Fig.1. It is due to the fact that the decks support directly the wheel loads that sometimes exceed the design ones. A load survey in Japan showed that there were trucks of about 378 kN (38 tons) and trailer trucks of about 666 kN (68 tons) [4], while the design truck loads are based on 196 kN (20 tons, T-20 truck) and 421 kN (43 tons, TT-43 truck), respectively[5].

This report shows a case study on fatigue assessment of orthotropic steel decks of box girder bridges typically used for urban highway systems. Cumulative fatigue damages for several welded joints are computed for the design wheel loads and for a series of model trucks representing actual truck traffic observed in the Hanshin Expressway [4], one of the major elevated urban highway systems in Japan.

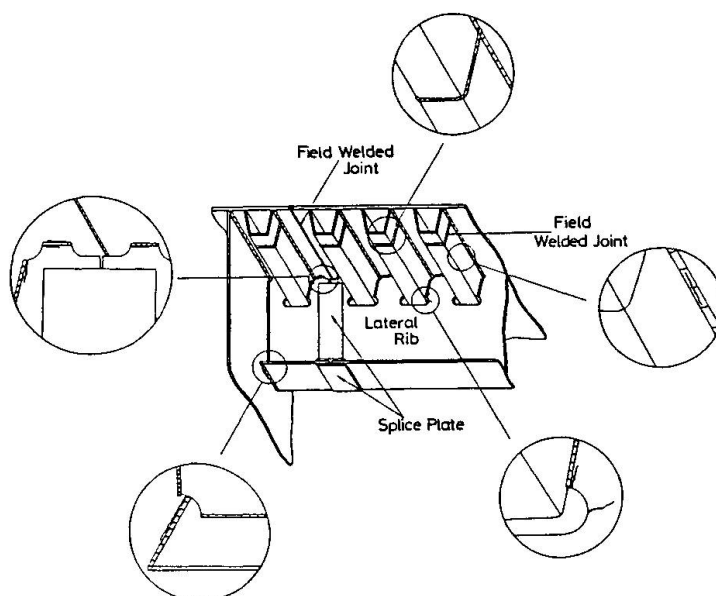


Fig.1 Example of fatigue cracks in orthotropic steel deck

2. FATIGUE ASSESSMENT OF ORTHOTROPIC STEEL DECKS

Fatigue assessment of orthotropic steel decks may be carried out by one of the following procedures.

(1) Assessment according to the design specifications

The current design specifications for the highway bridges [5] require fatigue assessment only for the orthotropic steel decks. The specifications give a few structural details and their fatigue allowable stress ranges corresponding to two million cycles. The stress ranges due to wheel loads should be less than these values [9]. The procedure is simple and feasible to most highway bridges. However, it seems insufficient when the decks are subjected to extremely heavy truck traffic with some overloadings.

(2) Assessment due to fatigue design load

An alternative way is to use an equivalent fatigue design loads, if any, which simulate the service loading condition. In order to compute the equivalent fatigue design loads, the weight and the frequency of the service loads are necessary. If the equivalent fatigue design loads are given as the fraction α of the static design loads, results for static design can be conveniently used for fatigue

assessment. The factor α is affected by the service load condition and the influence lines of the details of interest.

(3) Assessment using service loads

It seems more accurate when one can apply directly the service loads to the orthotropic steel decks and to count the resulted stress cycles. The stress cycles can be counted by the rainflow counting method and apply the Miner's cumulative damage rule. Because it needs accurate service loading prior to the computation and the computation is rather complex, it seems unrealistic to be used in design. However, the computed fatigue life seems reliable, when the reasonable S-N diagrams for the structural details are available.

(4) Assessment using measured service stresses

Recent development of so-called "Histogram Recorder" made it rather easy to measure service stresses in existing structures. Numerous measurements of service stresses in steel bridges were carried out throughout Japan [3]. The measured stress histograms can be used directly for fatigue assessment using the Miner's cumulative damage rule.

3. CASE STUDY ON FATIGUE ASSESSMENT OF ORTHOTROPIC STEEL DECKS

3.1 General Procedure

A part of a typical box girder bridge with orthotropic steel decks was selected and analyzed by grid theory. Design truck loads, T-20 and TT-43 trucks, and model truck loads that represent the service load condition are applied to the influence surfaces of the bending moments respectively to compute the resulting stress waves. The stress waves were then counted by the rainflow counting method and fatigue damages were computed by Miner's rule using appropriate design S-N curves.

3.2 Structural Analysis of Orthotropic Steel Decks

The model of the orthotropic steel decks was selected from "Typical Examples of Box Girder Bridge with Orthotropic Steel Decks," proposed by the Hanshin Expressway [6]. The bridge is consisted of two box girders of 72 m span carrying four-lane traffics, two lanes in each direction, as shown in Fig.2a. The grid analysis was carried out for a section of 12 m long with two cross beams and three lateral ribs of 3 m apart, as shown in Fig.2b. Influence surfaces were obtained for the structural details of interest.

The followings are the assumptions in the analysis.

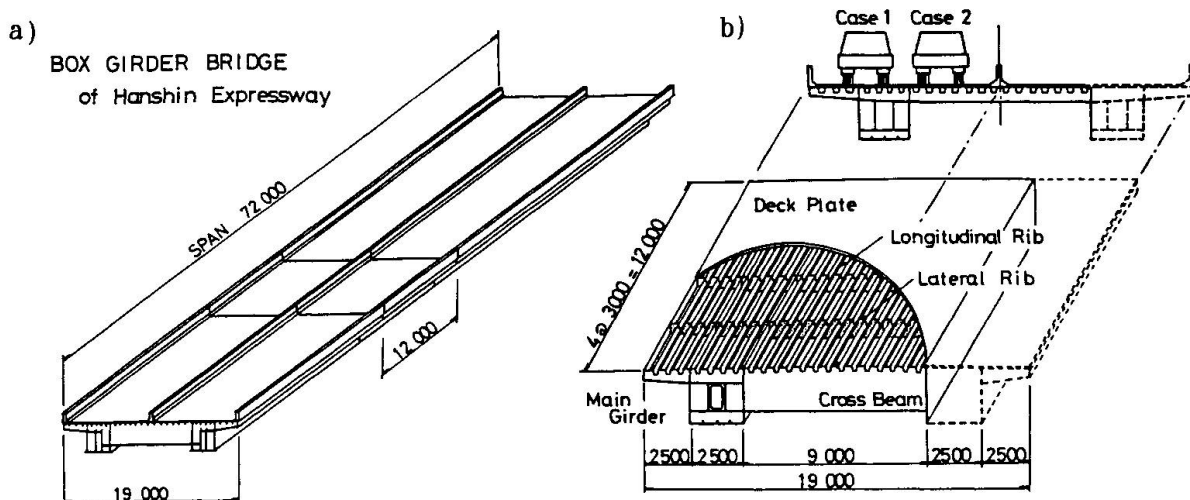


Fig.2 Analytical model of box girder bridge with orthotropic steel deck



- (1) The orthotropic steel decks were assumed as a grid that consists of trapezoidal ribs, lateral ribs, cross beams and main girders.
- (2) A box girder were divided into two I beams, each supporting the orthotropic steel decks at the upper end of the web.
- (3) The effective widths of the decks were computed according to the Design Specification of the Highway Bridges [5].

3.3 Structural Details

Fatigue assessments were carried out for six welded joints, as shown in Fig.3. The arrows in Fig.3 indicate the stress direction. The design S-N curves were selected from the fatigue design recommendation for the welded structure proposed by the European Convention for the Constructional Steelwork (ECCS) [7]. The detail categories are numbered in the recommendation according to their fatigue strength at two million cycles. The structural details and their detail categories used in the computation were as follows.

- (1) longitudinal fillet welds connecting trough ribs to deck; stress category 100.
- (2) lower ends of fillet welds between trough ribs and web of the lateral rib subjected to stresses in the longitudinal direction; stress category 80.
- (3) lower ends of fillet welds between trough ribs and lateral ribs with load carrying fillet welds; stress category 71 for toe crack and stress category 36 for root crack.
- (4) upper end of the fillet welds between trough ribs and lateral ribs; stress categories 71 and 36.
- (5) end of fillet welds between web of the lateral ribs and deck; stress category 71.
- (6) full penetration groove welds between lateral ribs and web of main girder; stress category 71.

The fatigue assessments were carried out for the details in the structures that showed the maximum range of bending moment, when the design loads, T-20 and TT-43, moved on slow lane and passing lane. Stresses were computed by the beam theory.

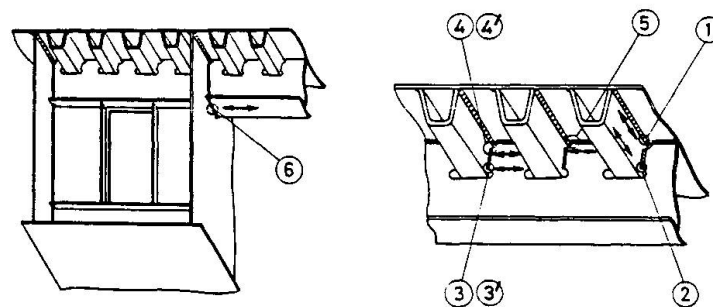


Fig.3 Welded joints for fatigue assessment

3.4 Computation of Stress Waves

The design truck loads and model truck loads were applied to the influence surfaces computed by the grid theory. The following assumptions were made in the analysis.

- (1) The wheel loads were assumed as concentrated loads and the impact factor was not considered.
- (2) The wheel loads passed on the same line, and the distribution in lateral direction was not considered.
- (3) A single truck passes on the deck at a time.
- (4) The truck passes either on the slow lane or the passing lane.

The stress ranges and the number of cycles were counted for those stress waves using rainflow counting method.

3.5 Design S-N Diagrams

The Miner's cumulative damage D can be expressed as follows:

$$D = \sum_{i=1}^k n_i / N_i \quad (1)$$

where n_i is the number of cycles of stress ranges σ_{ri} , N_i is the design fatigue life of the detail at σ_{ri} obtained from design S-N diagram, and k is the number of stress ranges of variable amplitude.

The following three types of design S-N diagrams can be used, as shown in Fig.4 [7, 8].

- I: A single S-N diagram of slope $m = 3$ is used. (Modified Miner's rule)
- II: When stress ranges are below the constant amplitude fatigue limit of the detail at five million cycles, slopes of the S-N diagrams are changed into $m = 5$.
- III: When stress ranges are below the cut-off limit at 100 million cycles, these stress ranges are neglected.

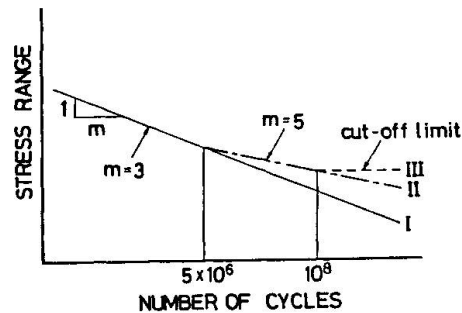


Fig.4 S-N diagram used for fatigue damage analysis

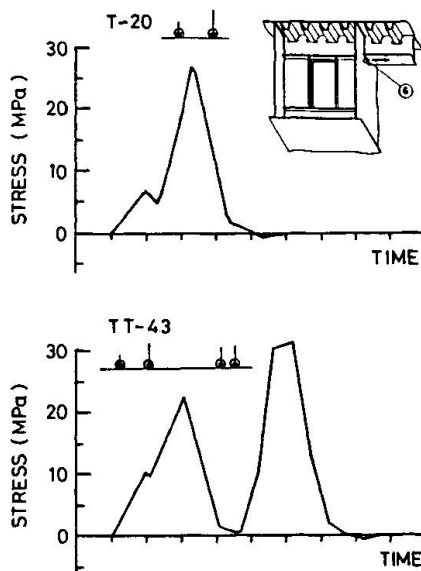


Fig.5 Stress wave due to model truck (lateral rib)

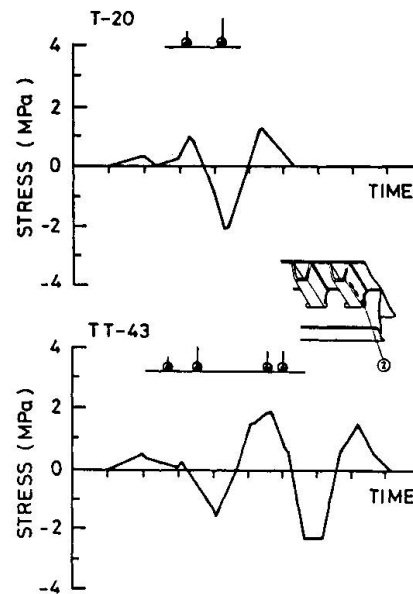


Fig.6 Stress wave due to model truck (longitudinal rib)



4. FATIGUE ASSESSMENTS FOR DESIGN TRUCKS

4.1 Stresses due to Design Truck, T-20 and TT-43

Computed stresses at the lateral ribs (detail No.6) due to T-20 and TT-43 trucks are shown in Fig.5. The T-20 truck has a wheel base of 4 m, which results in one large stress range per truck. On the contrary, the TT-43 truck gives two stress ranges per truck, because the distance between the front axle and the rear axle is about 7.8 m, and it is larger than the size of the influence surface of the details. The stresses at the longitudinal ribs (Detail No.2) are shown in Fig.6. The influence surface of this detail is small, and the fluctuating stresses appear for each passage of wheel.

4.2 Fatigue Damages

In order to compute fatigue damage due to the design trucks, design life and the number of design trucks passing on this bridge must be assumed. In this analysis

Table 1 Computed fatigue damage for design loads

Joint No.	Joint Classification (ECCS)	S-N Diagram	Fatigue Damage during 50 Years (4260/day/lane)		
			T-20		TT-43
			Case 1	Case 2	Case 2
①	100	I	no	no	no
		II	no	no	no
		III	0.0	0.0	0.0
②	80	I	no	3.0×10^{-3}	6.6×10^{-3}
		II	no	no	no
		III	0.0	0.0	0.0
③	71	I	no	no	no
		II	no	no	no
		III	0.0	0.0	0.0
③'	36	I	no	no	1.2×10^{-3}
		II	no	no	no
		III	0.0	0.0	0.0
④	71	I	no	3.4×10^{-3}	7.2×10^{-3}
		II	no	no	no
		III	0.0	0.0	0.0
④'	36	I	no	4.2×10^{-2}	9.1×10^{-2}
		II	no	no	2.1×10^{-3}
		III	0.0	0.0	0.0
⑤	71	I	no	6.0×10^{-3}	1.3×10^{-2}
		II	no	no	no
		III	0.0	0.0	0.0
⑥	71	I	no	2.33	4.96
		II	no	0.65	1.66
		III	0.0	0.0	1.40

no : Fatigue Damage less than 10^{-3} is considered no Fatigue Cracking Condition.

it was assumed that the design life was 50 years and the number of daily design trucks was 4260. It corresponds to the trucks that constitute 14.2 percent of the 30,000 vehicles passing daily on one lane.

The computed fatigue damages in 50 years of life span for six structural details are summarized in Table 1. When the T-20 truck passes on the slow lane (case 1),

the computed fatigue damages are less than 0.001. Although various assumptions are made in the analysis, one can safely conclude that these details are not susceptible to fatigue, with the design trucks passing on the slow lane.

The following discussion focuses only on the case 2, where the design trucks pass on the passing lane. The computed fatigue damages due to the TT-43 truck are about 2 to 2.5 times that of the T-20 trucks. It is due to the fact that the computed stresses are about the same for both trucks, while the TT-43 truck gives the number of cycles about twice of that from T-20 truck.

The lateral ribs connected to the main girder webs showed rather large fatigue damage, especially when the modified Miner's rule (S-N diagram I) is used. This is maybe because a diaphragm is usually fabricated in the box girder, outside of which cross ribs are welded and thus provides a structural discontinuity point for the cross ribs.

5. FATIGUE ASSESSMENT FOR SERVICE LOADS

5.1 Model Trucks Simulating Service Loads

Weights of all passing vehicles were measured for 24 hours by the Hanshin Expressway Public Authority in 1982 [4]. As shown in Table 2, about 72,000 vehicles passed, and 14.2 percent of them were trucks. The maximum weight of the trucks were 236 kN (24.1 tons) for the trucks with two axles, 370 kN (37.8 tons) with three axles, and 670 kN (68.4 tons) for trailer trucks. About 38 percent of the two axle trucks and about 49 percent of the trailer trucks weighed more than the design T-20 truck (196 kN or 20 tons, two axles). About 5 percent of trailer trucks weight more than the design TT-43 truck (421 kN or 43 tons, four axles).

Table 2 Classification of vehicles passing on Hanshin Expressway

Traffic Classification		Daily Traffic	Percentage
Large Vehicle	2 axles	1,630	2.3 %
	Tandem axle	3 axles(1)	4,926
		3 axles(2)	2,019
		4 axles	152
	Trailer	1,565	2.2 %
	Total	10,292	14.2 %
Middle Vehicle		12,913	17.8 %
Car		49,189	67.9 %
Total		72,394	100.0 %

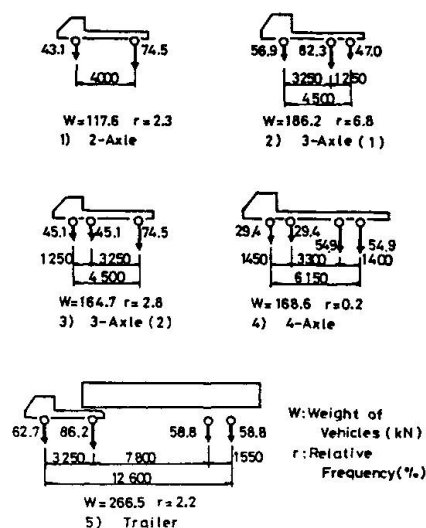


Fig.7 Model trucks representing service loading

The observed trucks were then re-grouped into five model trucks, as shown in Fig.7. They were; 1) two-axle truck; 2) three-axle truck with two rear axles; 3) three-axle truck with two front axles; 4) four-axle truck; and 5) trailer truck. The weights of the model trucks were computed using Eq.2.

$$W = \sum (f_i \cdot W_i^m)^{1/m} \quad (2)$$



where W_i is the measured truck weights and f_i is its relative frequencies. When $m = 3$ is used, W becomes so-called equivalent truck weights using modified Miner's rule. The wheel bases were also measured, and their mean values were computed, as shown in Fig.7. Each axle weight was also determined from the average axle weight ratio.

5.2 Computed Fatigue Damages and Equivalent Loads

The model trucks were applied to the passing lane, and fatigue damages for the six structural details were computed. It was assumed that the design life was 50 years and the average daily traffic was 30,000 vehicles in one lane. The results are summarized in Table 3. In general, for each structural detail, the three axle trucks with one front axle gives the most fatigue damages, owing to its relative frequency. The trailer trucks also gives large fatigue damages, because their weights are relatively large, and they usually gives more than two major stress ranges per truck.

Table 3 Computed fatigue damage due to model trucks
measured by Hanshin Expressway Public Authority

Joint No.	S-N Diagram	Fatigue Damage during 50 years (30,000/day/lane)						Model Load (kN)
		2 axles (2.3%)	3 axles(1) (6.8%)	3 axles(2) (2.8%)	4 axles (0.2%)	Trailer (2.2%)	Total (14.2%)	
①	I	6.7×10^{-7}	4.3×10^{-6}	8.4×10^{-7}	2.2×10^{-7}	3.7×10^{-6}	9.7×10^{-6}	110
	II	2.2×10^{-11}	2.9×10^{-10}	2.5×10^{-11}	1.8×10^{-11}	3.2×10^{-10}	6.8×10^{-10}	
	III	0.0	0.0	0.0	0.0	0.0	0.0	
②	I	3.5×10^{-5}	2.3×10^{-4}	4.5×10^{-5}	1.2×10^{-5}	2.0×10^{-4}	5.2×10^{-4}	110
	II	1.7×10^{-9}	2.2×10^{-7}	1.9×10^{-8}	1.4×10^{-8}	2.5×10^{-7}	5.2×10^{-7}	
	III	0.0	0.0	0.0	0.0	0.0	0.0	
③	I	9.6×10^{-7}	1.1×10^{-5}	1.5×10^{-6}	2.1×10^{-7}	3.6×10^{-6}	1.7×10^{-5}	144
	II	5.0×10^{-11}	1.3×10^{-9}	9.8×10^{-11}	2.1×10^{-11}	3.0×10^{-10}	1.8×10^{-9}	
	III	0.0	0.0	0.0	0.0	0.0	0.0	
③'	I	1.2×10^{-5}	1.3×10^{-4}	1.9×10^{-5}	2.7×10^{-6}	4.5×10^{-5}	2.1×10^{-4}	143
	II	3.4×10^{-9}	9.0×10^{-8}	6.6×10^{-9}	1.4×10^{-9}	2.0×10^{-8}	1.2×10^{-7}	
	III	0.0	0.0	0.0	0.0	0.0	0.0	
④	I	7.6×10^{-5}	8.3×10^{-4}	1.2×10^{-4}	1.7×10^{-5}	2.9×10^{-4}	1.3×10^{-3}	142
	II	7.3×10^{-9}	1.9×10^{-6}	1.4×10^{-7}	3.0×10^{-8}	4.3×10^{-7}	2.6×10^{-6}	
	III	0.0	0.0	0.0	0.0	0.0	0.0	
④'	I	9.5×10^{-4}	1.0×10^{-2}	1.5×10^{-3}	2.1×10^{-4}	3.6×10^{-3}	1.6×10^{-2}	142
	II	4.9×10^{-6}	1.3×10^{-4}	9.6×10^{-6}	2.0×10^{-6}	2.9×10^{-5}	1.8×10^{-4}	
	III	0.0	0.0	0.0	0.0	0.0	0.0	
⑤	I	1.3×10^{-4}	1.5×10^{-3}	2.2×10^{-4}	2.2×10^{-7}	5.1×10^{-4}	2.4×10^{-3}	144
	II	1.9×10^{-7}	5.0×10^{-6}	3.7×10^{-7}	1.8×10^{-11}	1.1×10^{-6}	6.7×10^{-6}	
	III	0.0	0.0	0.0	0.0	0.0	0.0	
⑥	I	0.04	0.43	0.06	7.2×10^{-3}	0.14	0.64	127
	II	2.6×10^{-3}	0.06	4.5×10^{-3}	7.3×10^{-4}	0.01	0.08	
	III	0.0	0.0	0.0	0.0	0.0	0.0	

() : Relative Frequency

The structural detail No.6, which is the lateral ribs welded to the main girders, showed the largest fatigue damage. This was the same trend as in the case of design truck loads. However, the fatigue damage was 0.64 in 50 years, even when the modified Miner's rule is used. It implies that the detail is not susceptible

to fatigue crackings, when the loading pattern and the number of vehicles remain the same over the assumed design life of 50 years.

The model truck loads give smaller fatigue damages than the design T-20 or TT-43 truck loads. It implies that the weight of the design truck can be reduced by the factor α , when one wants to obtain the same fatigue damages as the model loads. The reduced design truck loads are computed and summarized as equivalent loads in Table 3. It is concluded that the equivalent loads are between 54 and 75 percent of the weight of the T-20 trucks.

5.3 Fatigue Damage due to Different Daily Trucks and Truck Ratio

Fatigue damages were also computed for different daily traffic and different truck ratio. The weights and the wheel bases as well as the relative frequencies of the model trucks were assumed unchanged during the design life of 50 years. The fatigue damages were computed for the structural detail No.6, and plotted in Fig.8. The fatigue damages were mainly caused by the large vehicles, and the damage does not exceed unity when the total vehicles are 10,000 and the trucks are 40 percent of them (i.e. 4,000 trucks per day). On the contrary, when the total

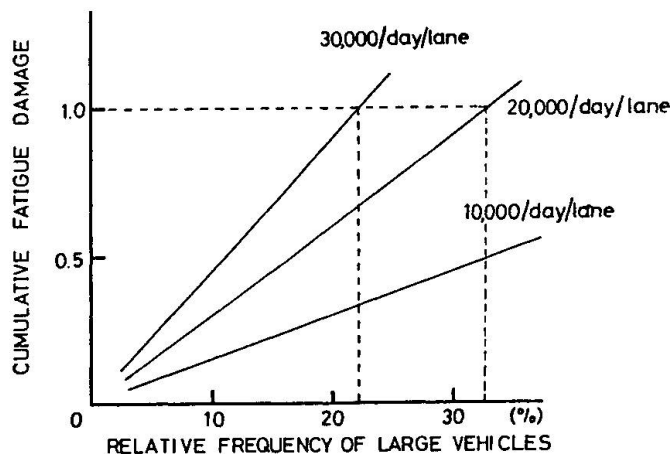


Fig.8 Effect of relative frequency of trucks on fatigue damage

vehicles is about 30,000, and the trucks are over 22 percent (i.e. 6,600 trucks per day), the damage exceeds unity. If the bridge carries 30,000 vehicles per day per lane and 44 percent of them are trucks, fatigue damage might exceed unity within 25 years at this detail.

6. SUMMARY OF FINDINGS

Fatigue damages were computed for the typical box girder bridge with the orthotropic steel decks using the design T-20 and TT-43 truck loads and the model truck loads. A part of the decks was analyzed and the stress waves were obtained by using grid theory. The fatigue damages were computed for six welded details in the structure using the Miner's cumulative damage rule. The followings summarize the findings.

- (1) The computed fatigue damages are normally larger when the trucks pass on the passing lane than on the slow lane.
- (2) The lateral ribs welded to the webs of the main box girders showed the largest fatigue damage when the design trucks were applied.
- (3) The model trucks, computed from the measured weights and the wheel bases by the Hanshin Expressway Public Authority, showed less fatigue damages than that due



to the design trucks. The fatigue damages were less than unity for all structural details with the current traffic condition, such as 30,00 vehicles per lane and 14.2 percent truck ratio.

(4) However, when the daily vehicles increase or when the number of trucks increase over the present condition, the computed fatigue damage may exceed the unity.

(5) The TT-43 truck gives about 2 to 2.5 times more fatigue damage than the T-20 truck, because the former gives two major stress ranges per truck for structural details of the orthotropic steel decks.

(6) When compared with the T-20 design trucks, the model trucks that represent the service condition of the Hanshin Expressway give fatigue damages between 0.16 and 0.40 depending on the structural details and the truck types. Therefore, the weight of the equivalent model trucks are about 54 to 75 percent that of the design T-20 truck.

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